Leading Effects in Hadroproductions of Λ_c and D From Constituent Quark-Diquark Cascade Picture

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Abstract

We discuss the hadroproductions of $\Lambda_c, \bar{\Lambda}_c, D$ and $\bar{D}$ in the framework of the constituent quark-diquark cascade model taking into account the valence quark annihilation. The spectra of Λ_c and $\bar{\Lambda}_c$ in $pA, \Sigma^- A$ and $\pi^- A$ collisions are well explained by the model using the values of parameters used in hadroproductions of D and $\bar{D}$. It is shown that the role of valence diquark in the incident baryon is important for $\bar{D}$ productions as well as for Λ_c production.

1 Introduction

Hadroproductions of charmed particles have been measured in fixed-target experiments [1, 2] and indicate the large leading/non-leading asymmetries, i.e. asymmetries between production cross sections of leading particles and those of non-leading particles defined as

$$A = \frac{\sigma(leading) - \sigma(non-leading)}{\sigma(leading) + \sigma(non-leading)}. \tag{1}$$

The leading particle shares a valence quark in common with the incident hadron, while the non-leading one does not. The leading particles are copiously produced at large Feynman x as compared with the non-leading particles in the forward region of the incident hadron. This is called as leading particle effect. For example, the asymmetry between $D^-(d\bar{c})$ and $D^+(c\bar{d})$ in $\pi^-(d\bar{u})$ interaction with a nucleon is defined as $A_{\pi^- N}(D^-, D^+) = (d\sigma(D^-) - d\sigma(D^+))/(d\sigma(D^-) + d\sigma(D^+))$ and increases from zero to nearly one with x in the π^- fragmentation region. In the conventional perturbative QCD at leading order (LO), the factorization theorem predicts that c and $\bar{c}$ quarks are produced symmetrically and then fragment into D and $\bar{D}$ independently. As a consequence, LO perturbative QCD predicts no asymmetry in contrast with the experimental data. The next to leading order (NLO) calculations generates asymmetries but they are much smaller than the data[3, 4].

To explain the leading/non-leading asymmetry, many attempts have been investigated: k_T factorization[5], string fragmentation[6, 7, 8], intrinsic charm contributions[9], recombination process with beam remnants[10, 11, 12, 13, 14, 15], recombination with participants in the hard scattering process[16, 17], recombination with surrounding light quarks in projectile and target[18], recombination using valon concept[19], light

quark fragmentation[20], meson cloud model[21] and so on. Productions of Λ_c and $\bar{\Lambda}_c$ in $\Sigma^- A$ [2, 22] and $\Sigma^- A, pA$ and $\pi^- A$ collisions[23] have been measured and analyzed in Refs.[13, 15, 17, 24] and [25]. These models explain the leading/non-leading asymmetry of charmed hadrons successfully, however, there are some uncertainties in the perturbative QCD calculations as reviewed in Refs.[26] and [27]. Hadronization of heavy quarks is still an open problem, since it is intrinsically non-perturbative process.

We have applied the covariant quark-diquark cascade model for hadroproductions of charmed mesons as well as hadrons composed u, d and s quarks[28, 29, 30, 31]. In the present paper, we investigate the hadroproductions of $\Lambda_c, \bar{\Lambda}_c, D$ and $\bar{D}$ and the leading/non-leading asymmetry in the framework of the constituent quark-diquark cascade picture and discuss the role of constituent diquark.

2 The model

2.1 Valence quark distributions in the incident hadron

We assume that a baryon is composed of a constituent quark and a constituent diquark, and a meson is composed of a constituent quark and a constituent anti-quark. The constituent quark (diquark) is a quark-gluon cluster consisting of the valence quark (diquark), sea quarks and gluons. Hereafter, we simply call them as quark and diquark. When the collision between the incident hadrons A and B occurs, it is assumed that the incident hadrons either break up into two constituents or emit gluons followed by a quark-antiquark pair creation. There are four interaction types: a) non-diffractive dissociation, b) and c) single-diffractive dissociations of B and A, and d) double-diffractive dissociation types as shown in Fig.1. The probabilities of these types to occur are $(1 - P_{gl})^2, P_{gl}(1 - P_{gl}), P_{gl}(1 - P_{gl})$ and P_{gl}^2, respectively. Here we denote the quark-antiquark pair emitted from A (B) via gluons as M_A (M_B). The probabilities of M_A (M_B) to be $u\bar{u}, d\bar{d}, s\bar{s}$ and $c\bar{c}$ are are denoted by $P_{u\bar{u}}, P_{d\bar{d}}, P_{s\bar{s}}$ and $P_{c\bar{c}}$, respectively.
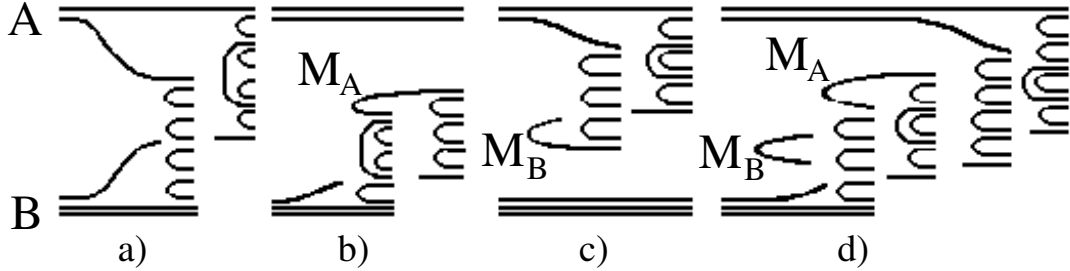

Figure 1: The interaction mechanism in AB collision: (a) Non-diffractive dissociation type, (b), (c) Single-diffractive and (d) double diffractive dissociation type mechanisms.

The light-like variables of A and B are defined as follows:

$$x_{0\pm}^A = \frac{E^A \pm p_{cm}}{\sqrt{s_0}}, \quad x_{0\pm}^B = \frac{E^B \mp p_{cm}}{\sqrt{s_0}}, \tag{2}$$

where $\sqrt{s_0} = E^A + E^B$ is the center of mass energy of the incident hadrons A and B. The momentum fractions of A, B and M_A for the process shown in Fig.1b are given as follows: The momentum fraction of M_A is fixed by the distribution function

$$H_{M_A/A}(z) = z^{\beta_{gl}-1}(1 - z)^{\beta_{ld}-1}/B(\beta_{gl}, \beta_{ld}), \tag{3}$$

and the uniform distribution R in the interval from zero to one as,

$$x_+^{M_A} = x_{0+}^A z, \quad x_-^{M_A} = x_{0-}^A R. \tag{4}$$

Then the momentum fractions of the incident particles A and B become as follows:

$$x_+^A = x_{0+}^A (1-z), \quad x_-^A = m_A^2/(x_+^A \, s_0),$$

$$x_-^B = x_{0-}^B - (x_-^A - x_{0-}^A (1-R)), \quad x_+^B = x_{0+}^B, \tag{5}$$

where the mass shell condition is considered and transverse momenta are neglected. Analogous expressions describe the momentum fractions of A, B and M_B for the process shown in Fig.1c , upon replacing superscripts $A \leftrightarrow B$ and subscripts $+ \leftrightarrow -$. The single-diffractive dissociation type mechanisms result in diffractive peaks of spectra of the same kind of the incident particles A and B at $|x| \approx 1$. The probability of the incident hadron to emit gluons followed by a quark-antiquark pair P_{gl} and the parameters β_{gl} and β_{ld} in (3) are chosen to reproduce the diffractive peaks of the spectra such as $\pi^\pm, K^\pm$ and p in $\pi^\pm p$, $K^\pm p$ and pp collisions at $|x| \approx 1$[30]. The parameters are chosen as $P_{gl} = 0.15, \beta_{gl} = 0.1$ and $\beta_{ld} = 3.0$. However, the main contributions to charmed hadrons come from the non-diffractive dissociation type mechanism.

The distribution functions of the constituents in the projectile A composed of a and a' are described as

$$H_{a/A}(z) = H_{a'/A}(1-z) = \frac{z^{\beta_a-1}(1-z)^{\beta_{a'}-1}}{B(\beta_a, \beta_{a'})}. \tag{6}$$

Similarly, the distribution function of q in M_A is given as $H_{q/M_A}(z) = z^{\beta_q-1}(1-z)^{\beta_q-1}/B(\beta_q, \beta_q)$. The dynamical parameters β's in (6), which determine the momentum sharing of the constituents, are related to the intercepts of the Regge trajectories as $\beta_u = \beta_d = 1 - \alpha_{\rho-\omega}(0) \approx 0.5$, $\beta_s = 1 - \alpha_\phi(0) \approx 1.0, \beta_c = 1 - \alpha_{J/\psi}(0) \approx 4.0$[32, 33]. For flavor anti-symmetric diquark $[qq']$ and symmetric diquark $\{qq'\}$, the dynamical parameters $\beta_{[qq']}$ and $\beta_{\{qq'\}}$ are chosen as $\beta_{[qq']} = \gamma_{[\ ]}(\beta_q + \beta_{q'})$ and $\beta_{\{qq'\}} = \gamma_{\{\}}(\beta_q + \beta_{q'})$, respectively. The commonly shared constituents of Λ_c with the incident p, Σ^- and π^- beams are ud-diquark, d and d-quark respectively. $\bar{\Lambda}_c$ has a commonly shared $\bar{u}$ quark with π^- and K^- beams and Λ_c is a non-leading particle in K^- beam. These distributions of the constituents in the incident hadrons affect the shapes of spectra of produced hadrons significantly. Hadrons are produced on the chain between a constituent valence quark(q_A)(anti-quark$(\bar{q}_A)$) from the incident hadron $A(M_A)$ and the constituent valence diquark$(qq_B(\bar{q}_B))$(quark(q_B)) from the incident hadron $B(M_B)$ for a meson-baryon collision as illustrated in Fig.1.

The small intrinsic transverse momenta of constituents in the incident hadrons are introduced by changing the direction of the incident constituents by an angle φ_{in} in the rest frame of the chain. Here we choose the distributions for $z = \cos\varphi_{in}$ as

$$D_{in}(z) = \frac{\beta_{in}+1}{2^{\beta_{in}+1}}(1+z)^{\beta_{in}} \tag{7}$$

in the region $-1 < z < 1$. Here we choose very small intrinsic transverse momenta and use the value $\beta_{in} = 40$ used in Ref.[31] in order to reproduce p_T^2 dependences of D mesons.

We take account of the annihilation of the valence antiquark from beam and valence quark from target in a slightly different way from the one pointed out in Refs. [10] and [11]. When the incident constituents in $A(M_A)$ and $B(M_B)$ are quark and its anti-quark, it is assumed that the annihilation process occurs with the probability P_{an} and the non-annihilation process occurs with $1 - P_{an}$. Let us consider the case of $\pi^- p$ collision. The annihilation process

$$\bar{u} + u \rightarrow \bar{q} + q \rightarrow "hadrons" + "hadrons" \tag{8}$$

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occurs with the probability P_{an}, when $\bar{u}$ in π^- interacts with u in p. Branching ratios of $\bar{u}u \to \bar{u}u, \bar{d}d, \bar{s}s$, and $\bar{c}c$ are chosen to be equal to $P_{u\bar{u}}, P_{d\bar{d}}, P_{s\bar{s}}$ and $P_{c\bar{c}}$ for the channels allowed energetically. The produced $\bar{q}$ and q in (8) are supposed to be non-free in terms of hadronization mechanism. Thus it is assumed that $\bar{q}$ has tendency to be produced in the forward direction of $\bar{u}$ in π^- beam. Therefore, here we choose the distributions for $z = \cos\varphi_{an}$ as

$$D_{an}(z) = \frac{\beta_{an}+1}{2^{\beta_{an}+1}}(1+z)^{\beta_{an}} \tag{9}$$

in the region $-1 < z < 1$, where φ_{an} is the angle between the directions of $\bar{u}$ and $\bar{q}$. To reproduce the $A_{\pi^- N}(D^0, \bar{D}^0)$, we choose the value $P_{an} = 0.2$ and use a value of $\beta_{an} = 20$ which roughly means $D_{an}(z) \sim \delta(z-1)$ [31].

2.2 Quark-diquark cascade process

Hadrons are produced on the cascade chain by processes

$$q \quad \to \quad M(q\bar{q}') + q', \tag{10}$$

$$q \quad \to \quad B(q[q'q'']) + \overline{[q'q'']}, B(q\{q'q''\}) + \overline{\{q'q''\}}, \tag{11}$$

$$\overline{[q'q'']} \quad \to \quad \overline{B}(\bar{q}\overline{[q'q'']}) + q, \tag{12}$$

$$\overline{[q'q'']} \quad \to \quad M(q\bar{q}') + \overline{[qq'']}, M(q\bar{q}') + \overline{\{qq''\}}, \tag{13}$$

$$\overline{\{q'q''\}} \quad \to \quad \overline{B}(\bar{q}\overline{\{q'q''\}}) + q, \tag{14}$$

$$\overline{\{q'q''\}} \quad \to \quad M(q\bar{q}') + \overline{[qq'']}, M(q\bar{q}') + \overline{\{qq''\}}, \tag{15}$$

where q denotes u, d, s and c and $[q'q'']$ does $[ud], [us], [uc], [ds], [dc], [sc]$ and so on. The symbols $[\ ]$ and $\{\ \}$ denote the flavor anti-symmetric and symmetric diquarks, respectively. Meson production probabilities from $q, \overline{[q'q'']}$ and $\overline{\{q'q''\}}$ are $1-\epsilon, \eta_{[\ ]}$ and $\eta_{\{\ \}}$, respectively. The parameter ϵ is the probability of baryon productions from a quark and is related to the baryon productions from π and K beams resulting in $\epsilon = 0.07$.[28] The processes (13) and (15) contribute to production of baryons which share no valence quark or diquark in common with the incident hadron. Although both Ω and $\bar{\Omega}$ share no valence quark common with the incident proton, the spectrum of Ω is harder than that of $\bar{\Omega}$ in the proton fragmentation region. In our model this is described as follows: after emitting K mesons through these processes, the incident diquark in the incident proton converts into $\{ss\}$ diquark and produce Ω by the process (14). The difference between the spectra of Ω and $\bar{\Omega}$ in pp collision is described by the processes (13),(15) and (14) and the parameters are chosen as $\eta_{[]} = \eta_{\{\}} = 0.25$.[28, 31]

For the cascade process $a \to H(a\bar{b}) + b$ in the beam (target) side, the distribution function of light-like fraction of b is assumed as

$$F_{ba}(z) = z^{\gamma\beta_a - 1}(1 - z)^{\beta_a + \beta_b - 1}/B(\gamma\beta_a, \beta_a + \beta_b) \tag{16}$$

and the light-like fraction of b becomes $x_+^b = zx_+^a$ $(x_-^b = zx_-^a)$. We fix the transverse momentum of the hadron H as a difference between two random points $\boldsymbol{p}_T^H = \boldsymbol{p}_{T2} - \boldsymbol{p}_{T1}$ with their lengths fixed by the distribution function

$$G(\boldsymbol{p}_T^2) = \frac{\sqrt{m_H}}{C}\exp(-\frac{C}{\sqrt{m_H}}\boldsymbol{p}_T^2) \tag{17}$$

in $\boldsymbol{p}_T^2$ space, where m_H denotes the mass of H. The parameter C is fixed from the experimental data on $\boldsymbol{p}_T^2$ distributions of pions[30]. We use the values of $\gamma = 1.75$ and $C = 1.8\text{GeV}^{-\frac{3}{2}}$, from previous analyses[30, 31].

We now see how the cascade processes occurs between the incident constituents, for example, q from A (M_A) and $\{q'q''\}$ from B. We redefine the light-like fractions of q and $\{q'q''\}$ in the rest frame of the incident constituents q and $\{q'q''\}$. The momentum sharing of the cascade process $q + \{q'q''\} \rightarrow H(q\bar{b}) + b + \{q'q''\}$ from q with $x_{\pm}^{q}$ and $\{q'q''\}$ with $x_{\pm}^{\{q'q''\}}$ takes place as follows[29, 34]: Using Eq.(16) with $a = q$, we fix the light-like fractions of b and $H(q\bar{b})$ as $x_{+}^{b} = x_{+}^{q}z$ and $x_{+}^{H} = x_{+}^{q} - x_{+}^{b}$, respectively and put $x_{-}^{b} = x_{-}^{q}$. The transverse momentum of H is fixed by Eq.(17). Then x_{-}^{H} is fixed from the onshell condition $x_{+}^{H} x_{-}^{H} = (m_{H}^{2} + \boldsymbol{p}_{T}^{2})/s'$, where $\sqrt{s'}$ is the subenergy of the incident q and $\{q'q''\}$ system. The transverse momentum of b is $\boldsymbol{p}_{T}^{b} = \boldsymbol{p}_{T}^{q} - \boldsymbol{p}_{T}^{H}$. The light-like fraction of $\{q'q''\}$ is decreased to $\tilde{x}_{-}^{\{q'q''\}} = x_{-}^{\{q'q''\}} - x_{-}^{H}$. If the energy of the $b + \{q'q''\}$ system is enough to create another hadron, the cascade process such as $b + \{q'q''\} \rightarrow b + H(c\{q'q''\}) + \bar{c}$ takes place in the opposite side. In the final step, we assume that the constituents recombine into one or two hadrons according to the processes: $q + \bar{q}' \rightarrow M(q\bar{q}')$, $q + [q'q''] \rightarrow B(q[q'q''])$, $\{qq'\} + \overline{[q''q''']} \rightarrow M(q\overline{q''}) + M(q'\overline{q'''})$ and so on. The momenta of the recombined hadrons are the sum of those of the final constituents and are offshell. In the cms of incident hadrons A and B, we have energy-momentum conservation relations $\sum_i \boldsymbol{p}_i = 0$ and $\sum_i p_i^0 = \sqrt{s_0}$, where $\boldsymbol{p}_i$ denotes the three momentum of i-th produced particle. In order to put recombined hadrons onshell, we multiply the three momenta of all produced hadrons by a common factor f so that the summation $\sum_i \sqrt{(f\boldsymbol{p}_i)^2 + m_i^2}$ would be equal to $\sqrt{s_0}$[30].

We take into account pseudoscalar (Ps), vector (V) and tensor (T) mesons. The production probabilities for them are assumed to be $P_{PS} = 1/9, P_V = 3/9$ and $P_T = 5/9$. For baryons we consider lower lying baryons: octet (B_8) and decuplet (B_{10}) baryons composed of u, d, and s flavors and the corresponding ones with charm flavor. Octet and decuplet baryons are described as

$$|B_8> = \cos\theta|q[q'q'']> + \sin\theta|q\{q'q''\}>, \tag{18}$$

$$|B_{10}> = |q\{q'q''\}> . \tag{19}$$

We assume the production probabilities for octet and decuplet baryons from symmetric diquarks to be $P_{B8} = 1/3$ and $P_{B10} = 1 - P_{B8} = 2/3$, respectively. Then the emission probabilities of individual cascade processes are determined from the above probabilities. For examples, the probabilities to produce $\pi^{+}, \rho^{+}, a_2^{+}, ..., \Delta^{++}, p, \Delta^{+}, ..., \Xi_{cc}^{++}$ and Ξ_{cc}^{*++} from a u quark are as follows:

$(1 - \epsilon) P_{d\bar{d}} P_{PS}, \quad (1 - \epsilon) P_{d\bar{d}} P_V, \quad (1 - \epsilon) P_{d\bar{d}} P_T, ...,$
$\epsilon P_{u\bar{u}}^{2}, \quad \epsilon P_{u\bar{u}} P_{d\bar{d}} \frac{1}{3} P_{B8} \sin^2\theta/(\frac{1}{3} P_{B8} \sin^2\theta + \frac{2}{3} P_{B10})$,
$\epsilon P_{u\bar{u}} P_{d\bar{d}} \frac{2}{3} P_{B10}/ (\frac{1}{3} P_{B8} \sin^2\theta + \frac{2}{3} P_{B10}), ...,$
$\epsilon P_{c\bar{c}}^{2} \frac{2}{3} P_{B8} \sin^2\theta/ (\frac{2}{3} P_{B8} \sin^2\theta + \frac{1}{3} P_{B10}),$
$\epsilon P_{c\bar{c}}^{2} \frac{1}{3} P_{B10}/ (\frac{2}{3} P_{B8} \sin^2\theta + \frac{1}{3} P_{B10}),$

where the factors 1/3 and 1/2 are flavor SU(4) factors. Directly produced resonances decay into stable particles.

The mixing angle of symmetric and anti-symmetric diquarks in octet baryon $\cos\theta$ and the pair creation probabilities of $u\bar{u}, d\bar{d}$ and $s\bar{s}$ are determined from the analyses of non-charmed hadron productions in πp, Kp and pp collisions. In Ref.[28], we used $\cos^2\theta = \frac{2}{3}$ and $P_{u\bar{u}} = 0.45$, $P_{d\bar{d}} = 0.45$ and $P_{s\bar{s}} = 0.10$. To reproduce the data on $\pi^- p \rightarrow D^{\pm}X$ cross section, we choose $\cos^2\theta = \frac{1}{2}, P_{c\bar{c}} = 0.0003$, $P_{u\bar{u}} = 0.435$, $P_{d\bar{d}} = 0.435$ and $P_{s\bar{s}} = 0.1297$[31]. The dynamical parameters $\gamma_{[\,]}$ and $\gamma_{\{\}}$ as well as the mixing angle of symmetric and anti-symmetric diquarks in octet baryon is related to the $\pi^{\pm}$ spectra in proton fragmentation region and are chosen as $\gamma_{[\,]} = 1.5$ and $\gamma_{\{\}} = 2.0$[30, 31].
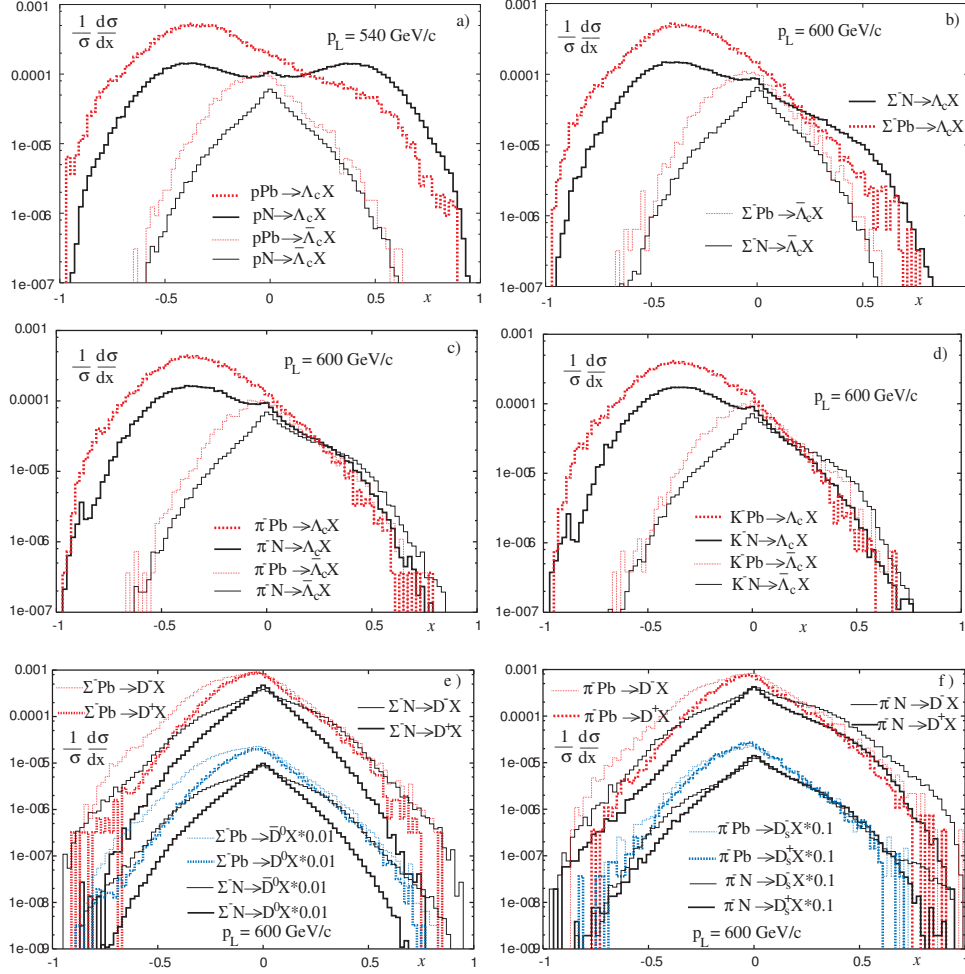
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Figure 2: Feynman x distributions of Λ_c^+ and $\bar{\Lambda}_c^-$ in a) p, b) Σ^-, c) π^-, d) K^- and charmed mesons distributions in e) Σ^- and f) π^- collisions with N and Pb targets.

2.3 Interaction with nucleus

We now consider hadron-nucleus interaction. We regard the hadron-nucleus collision as a sum of hadron-nucleon collisions and neglect the intra-nuclear cascade of produced hadrons. The projectile hadron successively collides with nucleons inside the nucleus. The probability $P_{hA}(\nu)$ that the incident hadron h collides with ν nucleons is calculated by the Glauber-type multiple collision model[29]. The number ν is determined by the distribution of nucleons in the nucleus and the cross section of the incident hadron with a nucleon σ_{hN}. We take the values $\sigma_{pN} = 40, \sigma_{\Sigma^-N} = 34, \sigma_{\pi^-N} = 24$ and $\sigma_{K^-N} = 21$mb in the hadron-nucleus collisions. The nucleon number density of the nucleus with a mass number A is assumed as

$$\rho(r) = \rho_0 \frac{A}{1 + \exp(\frac{r-r_A}{d})}, \tag{20}$$

where we choose $r_A = 1.19A^{\frac{1}{3}} - 1.61A^{-\frac{1}{3}}$ (fm) and $d = 0.54$ (fm). Then it is assumed that $M_1 N_1, M_2 N_2, ...,$
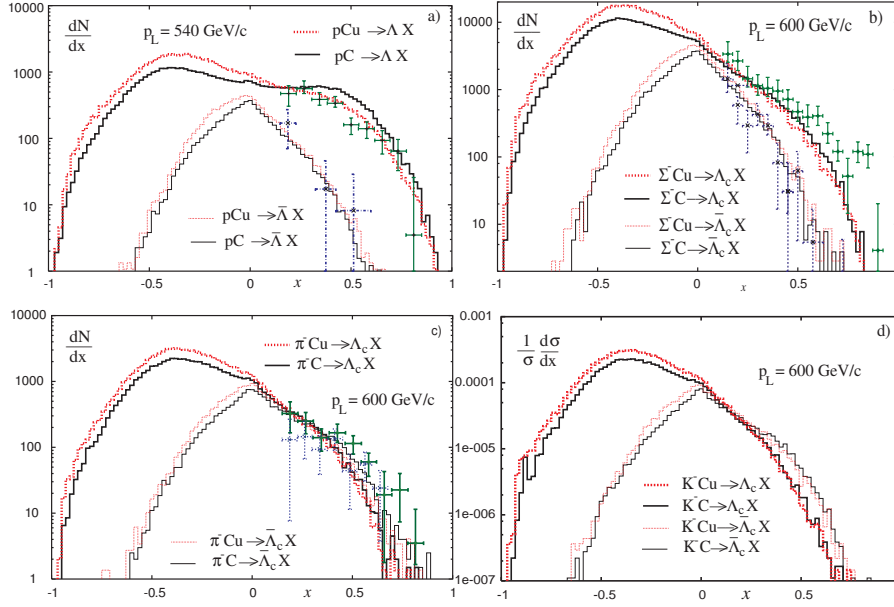
Figure 3: Feynman x distributions of Λ_c^+ and $\bar{\Lambda}_c^-$ in a) p, b) Σ^- , c) π^- and d) K^- collisions with C and Cu targets in arbitrary unit. The experimental data are taken from Ref. 21.

$M_{\nu-1}N_{\nu-1}$ and hN_ν interactions take place, where M_i is $q\bar{q}$ state emitted from h as M_A discussed in section 2.1. At each collision, the projectile hadron h looses its momentum. From the data on A dependences of the spectra of the projectile hadrons, we put the degradation rate of the momentum of h as $P(z) = 0.25 z^{0.25-1}$ which is used in Ref.[29].

3   Comparison with experiment

In this section, we give the results of our model for charmed hadron productions in p, Σ^-, π^- and K^- beam interactions with nuclei. To see the target mass number (A) dependence, we show the x distributions of $\Lambda_c, \bar{\Lambda}_c, D$ and $\bar{D}$ productions in p, Σ^-, π^- and K^- interactions with N and Pb targets at $p_L = 600$ GeV/c in Fig.2. All spectra increase with A in the region $x \overset{<}{\sim} 0$. The spectra of Λ_c become soft with A in the baryon beam fragmentation region. This is due to the momentum degradation of the incident baryon through the multiple interactions with nucleons in the target.

The spectra of $\bar{\Lambda}_c$ scarcely depend on A in the baryon beam fragmentation regions. In meson beam fragmentation regions, both Λ_c and $\bar{\Lambda}_c$ slightly depend on A and become soft with increasing A. In baryon beam fragmentation regions, A-dependences of the spectra of $\bar{D}$ mesons are smaller than those for D mesons. The shapes of the spectra for D mesons in baryon beam fragmentation regions are steep as compared with those of $\bar{D}$ mesons in baryon and D and $\bar{D}$ mesons in meson beam fragmentation regions.

In Fig.3, we show the x distributions of Λ_c and $\bar{\Lambda}_c$ in p, Σ^-, π^- and K^- beam interactions with C and Cu targets in arbitrary unit and compare the results with the experimental data E781[23]. The shapes of Λ_c and $\bar{\Lambda}_c$ in p, Σ^- and π^- fragmentation regions are well explained by our model. In our model, the shapes of the spectra are strongly related to the distributions of valence constituents in the incident hadrons, which are characterized by the parameters β's in (6). Diquarks in the incident baryons have a tendency to bring a large momentum fraction of the incident baryons. The valence constituents d and $\bar{u}$ in π^- beam have the same distribution i.e. energetic d and wee $\bar{u}$ or vice versa. The valence constituents
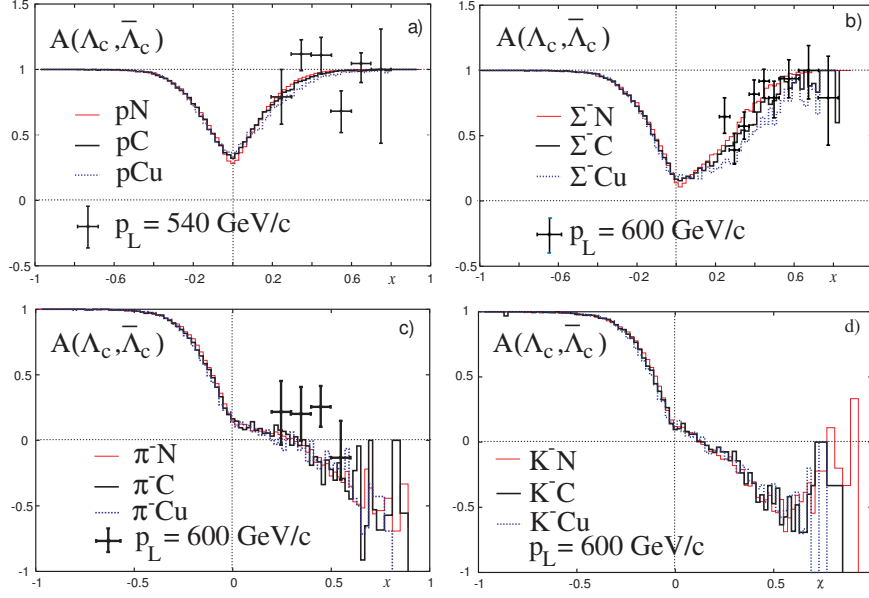
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Figure 4: Asymmetries between Λ_c^+ and $\bar{\Lambda}_c^-$ in a) p b) Σ^-, c) π^- and d) K^- collisions with C and Cu targets. The experimental data are taken from Ref. 21.

d and $\bar{u}$ in π^- are harder than the valence quarks in Σ^- and p beams. The ds diquark in Σ^- is harder than the ud diquark in p. The valence $\{ud\}$ diquark in p beam is the hardest among the commonly shared constituents between Λ_c and the incident p, Σ^-, π^- and K^- beams. Therefore x-distribution of Λ_c in proton beam is harder than those in other hadron beams.

The asymmetries between the spectra Λ_c and $\bar{\Lambda}_c$ in pA, Σ^-A, π^-A and K^-A collisions are shown in Fig.4. The results are in good agreement with the experimental data except for π^- beam. For π^- beam, Λ_c and $\bar{\Lambda}_c$ share the common valence constituents d and $\bar{u}$, respectively. Therefore the same spectra are expected for Λ_c and $\bar{\Lambda}_c$ productions in the region of π^- beam fragmentation. In our model, however, the excess of $\bar{\Lambda}_c$ over Λ_c is seen at $0.3 \stackrel{<}{\sim} x$. This is due to the fact that energetic Λ_c and $\bar{\Lambda}_c$ are produced in the d-quark-diquark and the $\bar{u}$-antiquark-quark chains, respectively. The former chain is slightly shifted to the target fragmentation region as compared with the latter one due to the large momentum fraction of the diquark[30]. Therefore our model gives the negative asymmetry $A_{\pi^-A}(\Lambda_c, \bar{\Lambda}_c)$ at $0.3 \stackrel{<}{\sim} x$. The valence diquark in Σ^- beam contributes to Λ_c production via a processes such as $ds \to du + K^- \to \bar{c} + \Lambda_c + K^-$ in Σ^- fragmentation region. The contributions to Λ_c production from the valence diquarks dominate the contributions from the valence quarks in Σ^- beam.

In Fig.5, We show the results of asymmetries between charmed and anti-charmed mesons in p and Σ^- interactions with N, C and Cu targets. The asymmetries $A_{pA}(D^-, D^+), A_{pA}(\bar{D}^0, D^0), A_{\Sigma^-A}(D_s^-, D_s^+)$ and $A_{\Sigma^-A}(D^-, D^+)$ are small as compared with the asymmetries $A_{pA}(\Lambda_c, \bar{\Lambda}_c)$ and $A_{\Sigma^-A}(\Lambda_c, \bar{\Lambda}_c)$. Although both D_s^+ and D_s^- in p and D^0 and $\bar{D}^0$ in Σ^- beam are non-leading particles, the results of asymmetries $A_{pN}(D_s^-, D_s^+)$ and $A_{\Sigma^-A}(\bar{D}^0, D^0)$ are non-zero and have large values. This is because in our model $\bar{D}$ mesons are produced mainly from the chain between the valence diquark in the incident baryon and the valence quark in the target nucleon. For example, D_s^- in proton fragmentation region is produced via a process such as $ud \to sd + K^+ \to cd + D_s^- + K^+$. The more energetic the valence diquark becomes, the more copiously $\bar{D}$ mesons are produced in the baryon fragmentation region. In our model the valence ds diquark in Σ^- beam has a larger momentum fraction than the valence diquarks in p beam. Consequently the asymmetries $A_{\Sigma^-A}(\bar{D}^0, D^0)$ are large as compared with $A_{pA}(D_s^-, D_s^+)$. The
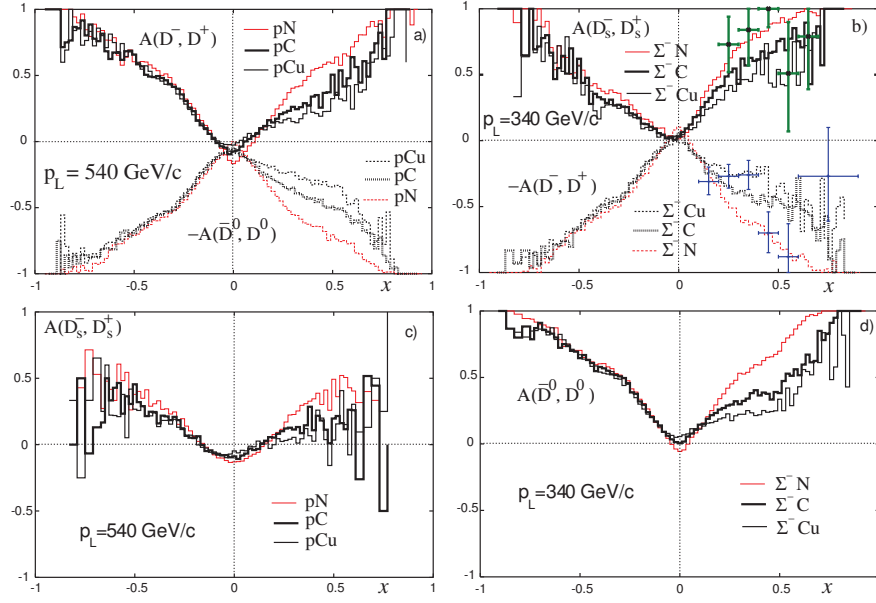
Figure 5: Asymmetries $A(D, \bar{D})$ between leading and non-leading charmed mesons in a) pA and b) $\Sigma^- A$ collisions. Asymmetries between non-leading charmed mesons in c) pA and d) $\Sigma^- A$ collisions. The experimental data are taken from Ref. 20.

asymmetry $A_{\Sigma^- A}(D_s^-, D_s^+)$ is larger than other charmed meson asymmetries in p and Σ^- beams. This is also due to the large momentum fraction of the valence ds diquark in Σ^-. In the target fragmentation region, both D and $\bar{D}$ mesons increase similarly with the mass number A and the asymmetries show small mass number dependences. Since the spectra of D mesons increase with A and those of $\bar{D}$ mesons change little, there are considerable target mass number dependence in the asymmetries $A(\bar{D}, D)$ at $0 \stackrel{<}{\sim} x$.

4 Conclusions

1. We have examined hadroproductions of charmed baryons in the frame work of the quark-diquark cascade model. Their spectra are well explained by using the values of the dynamical parameters fixed from Regge intercepts. The large leading/non-leading asymmetries $A_{pA}(\Lambda_c, \bar{\Lambda}_c)$ and $A_{\Sigma^- A}(\Lambda_c, \bar{\Lambda}_c)$ are naturally explained.

2. The valence diquark in the incident baryon, which brings a large momentum fraction of the beam, plays an important role for $\bar{D}$ productions as well as for Λ_c production[28]. The non-leading anti-charmed meson productions in baryon beams are largely affected by the valence diquark distribution in the incident baryons through the processes (13) and/or (15).

3. In meson beam fragmentation regions, A-dependences of the spectra of non-leading charmed mesons are small as compared with those for leading charmed mesons. There are considerable A-dependences in Λ_c and D meson productions, while those for $\bar{\Lambda}_c$ and $\bar{D}$ productions are small in baryon beam fragmentation regions.

4. There are discrepancies between the data and calculations of asymmetries $A_{\pi^- A}(\Lambda_c, \bar{\Lambda}_c)$ at π^- fragmentation region as seen above. Piskounova discussed this problem successfully by introducing the transfer of string junction in quark-gluon string model[25]. To explain the experimental data in our model, it is necessary, for example, a energetic d quark from π^- beam and a wee uc diquark from target

nucleon to recombine into a Λ_c. Here the uc diquark is converted from the valence diquark in the target nucleon by emitting several mesons through the processes (13) and/or (15). The significant value of the asymmetry $A_{\pi^- A}(\Lambda_c, \bar{\Lambda}_c)$ as well as the small value of $A_{\pi^- N}(D^0, \bar{D}^0)$ in meson beam fragmentation is a challenging problem.

Acknowledgments

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